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Numerical Simulation on Effect of Porous Medium on Mixed Convection Heat Transfer in a Ventilated Square Cavity

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Abstract

The aim of the present numerical study is to investigate the effect of adding porous media to a ventilated square cavity, on the mixed convection heat transfer. The top wall of the enclosure is kept at constant temperature and the bottom wall is located at constant heat flux. The right and left walls are kept to be adiabatic. An external flow entering to the cavity from a port in left vertical wall and leaving from a port at right vertical wall. The finite volume method is used to discretize the governing equations and they solved with SIMPLE algorithm. In this article, the effects of the Richardson number and the Darcy number on the fluid flow and heat transfer rate have been studied. The obtained results showed that the increasing Darcy number and porous particles diameter, causes a decreasing trend of the heat transfer rate.

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Keywords: Mixed convection; ventilated cavity; Darcy number; Richardson number

1. Introduction

Numerical and experimental studies on the fluid flow in cavities filled with porous media are prevalent for an

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extensive range of conditions varying from environmental applications to inkjet printing technology. Many researchers investigated numerical and experimental works on porous media. Since the early works by researchers [1,2,3], also a great deal of researches was devoted to study this phenomenon. The fundamental interest comes from the concern to understand the mass transfer mechanism [4,5]and fluid flow behavior through variable porosity of the media [6]. On the other hand, a similar interest was caused by the extensive range of engineering applications by using of this type of phenomenon [7,8]. Khanafer and Chamkha [9] have done a numerical investigation to study the mixed convection heat transfer in a cavity filled with a Darcian fluid-saturated uniform porous medium with a lid-driven wall in the presence of internal heat generation. Oztop [10] studied a numerical work to investigate the mixed convection heat transfer in a lid-driven and partially heated cavity filled with porous media. He utilized the finite volume method to investigating the effects of position of partial heater on the mixed convection heat transfer and fluid flow characteristics. His results showed that the positions of partial heater can be used as control parameter for heat and fluid flow. Mahmud and Pop [11] did a study to investigate the mixed convection heat transfer in a ventilated cavity filled with a porous medium. In their case, inlet and outlet ports were located in bottom and top walls and flow motion have a similar appearance to lid-driven cavity flow. Khanafer and Vafai [12] studied a numerical work to investigate the double-diffusive mixed convection heat transfer in a lid-driven cavity filled with porous media. They found that the buoyancy ratio, Darcy number, Lewis number, and Richardson number have significant effects on the double-diffusive mixed convection heat transfer.
A review on some of the studies mentioned in this part, about the mixed convection heat transfer in cavities shows that very few works have been done on this context. Hence the present study deals the impact of effective parameters on the mixed heat transfer in the ventilated cavity. In the other words; it is assumed that the square cavity with inlet and outlet ports is filled with Incompressible base fluid. Therefore various factors which may affect the increasing of heat transfer on the hot side wall were discussed. Hence the effect of adding porous media on heat transfer of the hot side wall in a cavity with inlet and outlet ports has studied in this paper.

2. Governing equations and problem formulation

The geometry used in this article can be seen in Fig. 1. To find ways to increase the heat transfer, the effect of adding porous media on this geometry had considered.
As it is shown in Fig. 1 the geometry is a two-dimensional square cavity with hot bottom horizontal wall held on constant heat flux and cold upper horizontal wall with constant temperature (T_L) and assumed to be insulated (q" = 0). Also left and right vertical walls kept insulated. Inlet of the cavity is located on the bottom of the left side wall and the outlet is on the top of the right side wall. The ratio of the size of inlet or outlet ports to the length of the cavity is assumed 0.1.

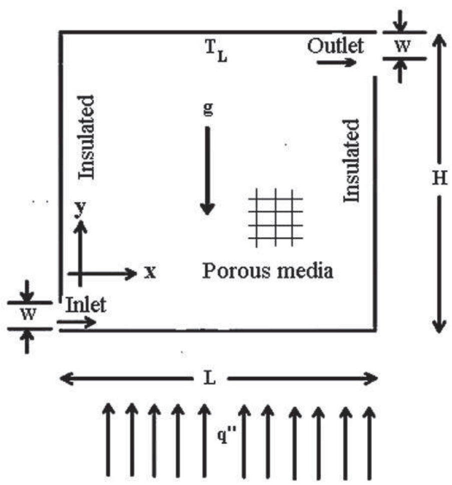


Fig. 1. Schematic of ventilated cavity

To simulating this problem the flow is considered incompressible, steady, Newtonian and laminar. The viscous dissipation in the energy equation has been neglected. Moreover, it is considered that all of properties except the density are constant. The density varies according to the Boussinesq approximation.

Some dimensionless variables which are shown in relation (1) are used to find the dimensionless form of the governing equations.

$$X=\frac{x}{L},Y=\frac{y}{L},U=\frac{u}{u_i},V=\frac{v}{u_i},\ \ \theta=\frac{(T-T_L)k}{q"L},P=\frac{p}{\rho {u_i}^2} \tag{1}$$

The dimensionless form of the governing equations (continuity, momentum and energy equations) for laminar and steady state mixed convection fluid flow and heat transfer with the Boussinesq approximation in y-direction are as following:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{2}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{\partial P}{\partial X}+\varepsilon\frac{1}{Re}\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}\right)-\varepsilon^2\frac{1}{ReDa}U \tag{3}$$

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{\partial P}{\partial Y}+\varepsilon\frac{1}{Re}\left(\frac{\partial^2 V}{\partial X^2}+\frac{\partial^2 V}{\partial Y^2}\right)-\varepsilon^2\frac{1}{ReDa}V+Ri\theta \tag{4}$$

$$U\frac{\partial \theta}{\partial X}+V\frac{\partial \theta}{\partial Y}=\frac{1}{Re\ Pr}\left(\frac{\partial^2 \theta}{\partial X^2}+\frac{\partial^2 \theta}{\partial Y^2}\right) \tag{5}$$

Where ε, is the porosity of the medium.
The dimensionless parameters in these equations are defined as:

$$\mathrm{Pr}=\frac{\upsilon}{\alpha},\mathrm{Re}=\frac{u_i L}{\upsilon}\ \ ,\ \ \mathrm{Ri}=\frac{\mathrm{Gr}}{\mathrm{Re}^2},Da=\frac{K}{L^2},K=\frac{1}{180}\frac{\varepsilon^2{d_p}^2}{(1-\varepsilon)^2} \tag{6}$$

Where Pr, Re, Gr, Ri, Da and K are Prandtel number, Reynolds number, Grashoff number, Richardson number, Darcy number and the permeability of fluid which can be related to dimensionless parameter of Darcy number, respectively.

The dimensionless boundary conditions for the present problem are specified as follows:
Inlet port:

$$\mathrm{u}^*=1\ \ ,\mathrm{v}^*=0\,,\theta=0 \tag{7}$$

Outlet port:

$$\frac{\partial \mathrm{u}^*}{\partial \mathrm{X}}=0,\frac{\partial \mathrm{v}^*}{\partial \mathrm{X}}=0,\frac{\partial \theta}{\partial \mathrm{x}^*}=0 \tag{8}$$

Left solid wall:

$$\mathrm{u}^*=0\ \ ,\mathrm{v}^*=0\,,\frac{\partial \theta}{\partial \mathrm{x}^*}=0 \tag{9}$$

Right solid wall:

$$u^* = 0 \ , v^* = 0 \, , \frac{\partial \theta}{\partial x^*} = 0 \tag{10}$$

Top solid wall:

$$u^* = 0 \ , v^* = 0 \, , \theta = 0 \tag{11}$$

Bottom solid wall:

$$u^* = 0 \, , v^* = 0 \, , \frac{\partial \theta}{\partial y^*} = 1 \tag{12}$$

The local Nusselt number over the heat transfer walls is calculated by:

$$\mathrm{Nu} = \frac{hL}{k} , h = \frac{q_0^{"}}{T_s - T_L} , \mathrm{Nu} = \frac{1}{\theta_s} \tag{13}$$

The mean Nusselt number over the hot wall is:

$$Nu_m = \frac{\int Nudn}{\int dn} \tag{14}$$

In this study the governing equations have been discretized numerically using the finite volume method and by utilizing the SIMPLE algorithm to be coupled the velocity and pressure in the momentum equation [13]. The converging for solution is assumed as differences between two successive iterations was less than 10^{-7} for every equation and every discrete control volume. A square cavity was assumed as the solution domain. Finally a 101×101 uniform grid is selected for square cavity because it is fine enough to obtain precise results; the numerical results were compared with those presented in Mohdirwan et al. [14] to validating the present numerical model.

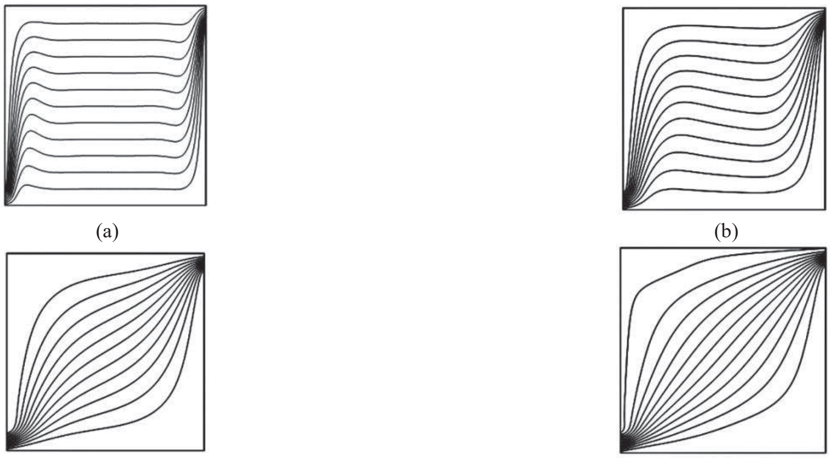
3. Results and discussion

As mentioned in introduction, the effect of adding porous media to the cavity which is filled with incompressible base fluid on increasing the magnitude of the mixed convection heat transfer on the hot wall in a square ventilated cavity had studied. Dimensionless parameters used in the simulation are: The Rayleigh number (Ra) which is assumed 10^4, the Richardson number (Ri) changes from 10^{-1} to 10, Darcy number (Da) changes from 10^{-2} to 10^{-5}, diameter of the porous materials (dp) are assumed 10^{-4} and 10^{-3} and Prandtl number is assumed 6.8 (Pr=6.8).

3.1. The effect of porous medium

In this section, the effect of some dimensionless parameters such as Richardson number and Darcy number, the level of the porosity and the diameter of the porous materials on heat transfer and fluid flow inside of the cavity have considered.

Figure2 shows the effect of variation of Darcy number on flow lines at Richardson number equal to 0.1.



(a) (b)

(c) (d)

Fig. 2. The effect of porous media on flow lines contours at $Ra=10^4$, $dp=10^{-4}$, $Ri=0.1$ and a) $Da=10^{-5}$; b) $Da=10^{-4}$; c) $Da=10^{-3}$; d) $Da=10^{-2}$.

As it is illustrated in Fig. 2, by increasing the Darcy number which means more porous in medium, the fluid permeability in the porous layer increases and the flow through the porous layer meets little resistance, on the other hand by decreasing the Darcy number as it is shown in Fig. 2.a, the fluid permeability in the porous layer would be low and the flow through the porous layer meets high resistance, hence the fluid distributes in entire space of the cavity. In the other words by increasing the Darcy number as it is shown in Fig. 3, the velocity increases.

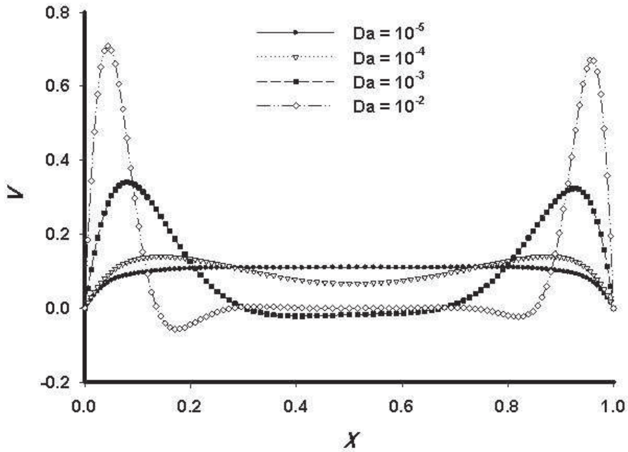


Fig. 3. The effect of increasing Darcy number on dimensionless velocity profile at $Y=0.5$, $Ri=0.1$ and $dp=10^{-4}$.

The effect of velocity on the mean Nusselt number can be explained due to the coupling of temperature and velocity, by increasing the velocity, temperature field decreases. According to relation (13) as a result, the mean Nusselt number increases as the Darcy number increases.

The variation of the mean Nusselt number based on Darcy number in two different diameters 10^{-3} and 10^{-4}can is seen in Figs. 4 and 5.

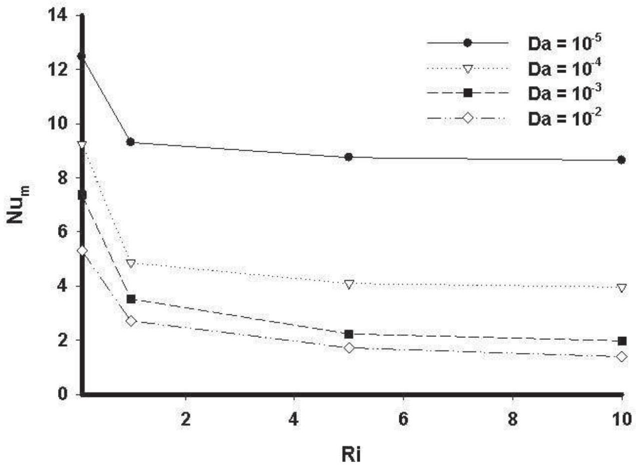


Fig. 4. The effect of variation of Darcy number on the mean Nusselt number at different Richardson numbers, $Ra=10^4$ and $dp=10^{-3}$.

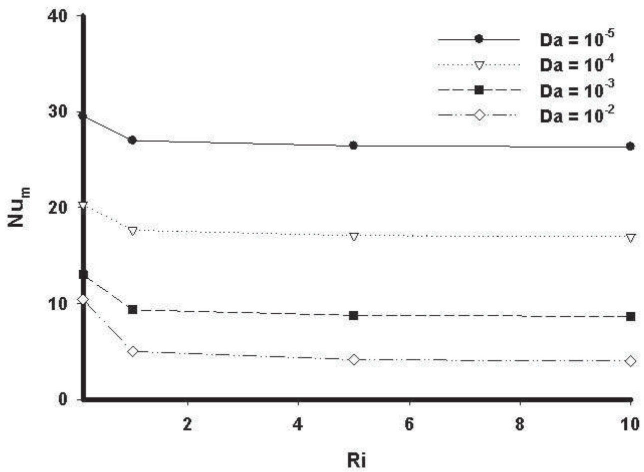


Fig. 5. The effect of variation of Darcy number on the mean Nusselt number at different Richardson numbers, $Ra=10^4$ and $dp=10^{-4}$.

As can be seen in Figs 4 and 5, the mean Nusselt number increases as the Darcy number increases. As mentioned before, this result can be achieved by temperature decreasing and using of relation (13) too.

Figure 6 shows the variation of the mean Nusselt number based on the Richardson number in two different particle sizes. As it is illustrated in Fig.6 the mean Nusselt number decreases as the diameter of the particles increase.

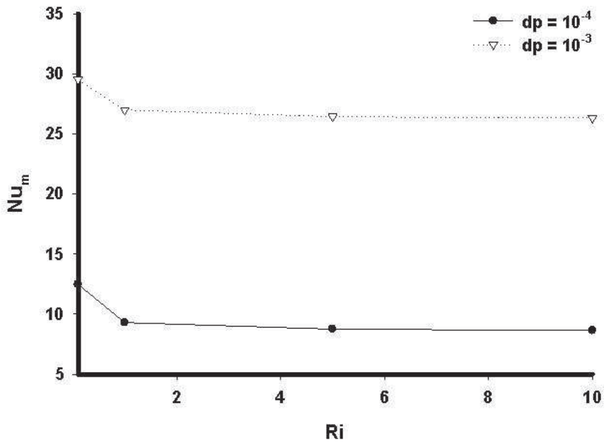


Fig. 6. The variation of the mean Nusselt number based on the Richardson number in two different particle sizes, $Ra=10^4$ and $Da=10^{-2}$.

The isothermal lines contours in two different diameters of the particles are shown in Fig. 7. As it is evident in Fig.7 as the diameter of the particles increases, the thickness of the thermal boundary layer decreases and as a result, the temperature of the hot wall increases. Hence according to relation (13) the mean Nusselt number decreases.

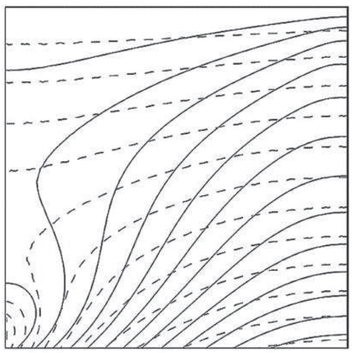


Fig. 7. The isothermal lines contours in two different diameters of the particles, $Ra=10^4$, $Ri=5$, $Da=10^{-2}$, $dp=10^{-2}$ (line) and $dp=10^{-3}$ (Dash line).

4. Conclusion

This paper presents the results of a numerical investigation on the mixed convection heat transfer within a ventilated square cavity that allows entering and exiting fluid.
The following results were obtained from numerical simulation:

- By increasing the Darcy number which means more porous in medium, the fluid permeability in the porous layer increases and the flow through the porous layer meets little resistance, so the velocity increases and due to the coupling of temperature and speed, by increasing the velocity, temperature field decreases. According to relation (13) as a result, the men Nusselt number by increasing the Darcy increases.
- By increasing the diameter of the particles, the thickness of the thermal boundary layer decreases thus the temperature of the hot wall increases and as a result According to relation (13) the mean Nusselt number decreases.

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